ISOSPIN SYMMETRY BREAKING IN MIRROR NUCLEI ^{23}Mg–^{23}Na*

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Mirror energy differences (MED) are a direct consequence of isospin symmetry breaking. Moreover, the study of MED has proved to give valuable information of several nuclear structure properties. We present the results of an experiment performed in GANIL to study the MED in mirror nuclei ^{23}Mg–^{23}Na up to high spin. The experimental values are compared with state-of-the-art shell model calculations. This permits to enlighten several nuclear structure properties, such as the way in which the nucleons alignment proceeds, the radius variation with J, the role of the spin-orbit interaction and the importance of isospin symmetry breaking terms of nuclear origin.

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1. Introduction

Nuclei located at or close to the $N = Z$ line are the ideal region in the Chart of Nuclides where it is possible to find answers to some fundamental problems in nuclear physics, such as the isospin symmetry of the nuclear interaction. One of the consequences of this symmetry is that the level schemes of mirror nuclei (obtained interchanging neutrons and protons) should be identical.

The differences between the excitation energy of analogue states, called mirror energy differences (MED), are therefore an important signature of isospin symmetry breaking.

Although the Coulomb interaction is the main responsible of this asymmetry, it has been pointed out that Isospin Symmetry Breaking (ISB) terms could arise from the residual nuclear interaction [1].

Systematic studies in the $f_{7/2}$ shell have shown that MED constitute a very delicate probe of the nuclear structure, being sensitive to the nucleon alignment, the radius variation with increasing J and the wave function configuration [2].

The extension of these investigations to other mass regions is very important to check the limits of validity of the isospin symmetry for different masses and to search for other isospin breaking effects.

What we have learned from the systematic studies in the $f_{7/2}$ shell relies on the good amount of experimental data and the excellent shell model description of the structure of these nuclei [3]. Another mass region where the shell model reproduces with a good accuracy the experimental data is the lower *sd* shell.

The experiment presented here intended to study the MED in $T = 1/2$ mirror nuclei ^{23}Mg–^{23}Na up to high spin.

2. Experimental method

The experiment has been performed at the CIME accelerator at GANIL. High spin states in ^{23}Mg–^{23}Na have been populated with the fusion-evaporation reactions $^{12}\mathrm{C}(^{16}\mathrm{O}, \alpha n)$ and $^{12}\mathrm{C}(^{16}\mathrm{O}, \alpha p)$, respectively; the ^{16}O beam at 60–70 MeV impinged on a self-supported carbon target of 500 μg/cm^2.

The light charged particles evaporated from the ^{28}Si compound nucleus have been detected by the 4π DIAMANT detector, composed of 80 CsI(Tl) scintillators, what permits to achieve an excellent discrimination between alphas and protons. The NEUTRON WALL array, consisting of 50 closely packed liquid scintillators, was placed at forward angles with respect to the beam direction, covering $\sim 1\pi$ of the total solid angle. These ancillary devices allowed to cleanly select the evaporation channels of interest, (αp) and (αn). The γ rays produced in the reaction have been detected by the γ-ray array EXOGAM which in this experiment was composed of 10 Compton suppressed clovers of 4 segmented HPGe detectors each, placed at 15 cm from the target to allow a good Doppler correction. Seven clovers were placed at 90°, and three clovers at 135° with respect to the beam line.

3. Results and discussion

The excellent channel selection given by the ancillary detectors and the possibility to perform γ–γ coincidences allowed to clearly observe the γ-ray transitions of the nuclei of interest. In the present work, the previously known transitions [4] have been observed and confirmed up to the highest spin values. Moreover, new transitions have been identified in ^{23}Mg, extending both the *yrast* and *yrare* bands up to $J = \frac{15}{2}^+$. The new level schemes for mirror nuclei ^{23}Mg–^{23}Na are presented in Fig. 1, where only the most intense transitions, relevant for the following discussion, are reported.

The experimental MED have been compared with shell model calculations performed with the code ANTOINE, following the method adopted in [3]. The USD interaction in the $d_{5/2}$–$s_{1/2}$–$d_{3/2}$ valence space has been used. Corrections to the single-particle energies of protons and neutrons induced by the electromagnetic spin-orbit interaction E_{EMSO} and the E_{ll} term described in [3] have been taken into account. The contribution of the multipole Coulomb interaction V_{CM}, which is sensitive to the recoupling of valence protons with varying J, has been included using Coulomb matrix elements obtained in the harmonic oscillator basis. The effect of the changes in the nuclear radius as a function of the angular momentum has been estimated from the variation of occupation number of the $s_{1/2}$ orbital with increasing J. Systematic studies in the $f_{7/2}$ shell have shown that electromagnetic ISB terms are insufficient to reproduce the experimental values, and an additional isospin non-conserving term of non-Coulomb origin, called V_B, has to be introduced (the so-called $J = 2$ *Anomaly*). To take into account this effect, a schematic interaction, in which the only non-null matrix element is the one corresponding to two protons coupled to $J = 2$ in the $d_{5/2}$ and $d_{3/2}$ shells, has been used. The contribution of the different terms of the MED are reported in Fig. 2.

The trend of the experimental MED is well-reproduced by the Coulomb multipole term V_{CM} which is sensitive to the alignment of valence protons: it is well-known that the recoupling of a pair of particles to higher values of angular momentum implies a reduction of the overlap between their wave functions, causing a reduction of the Coulomb energy. Since when a nucleus aligns protons, its mirror aligns neutrons, this affects the MED. On the other hand, it is clear that the radial term V_{Cm} is needed to improve the agreement with the experimental data. This confirms the crucial role played by the $s_{1/2}$

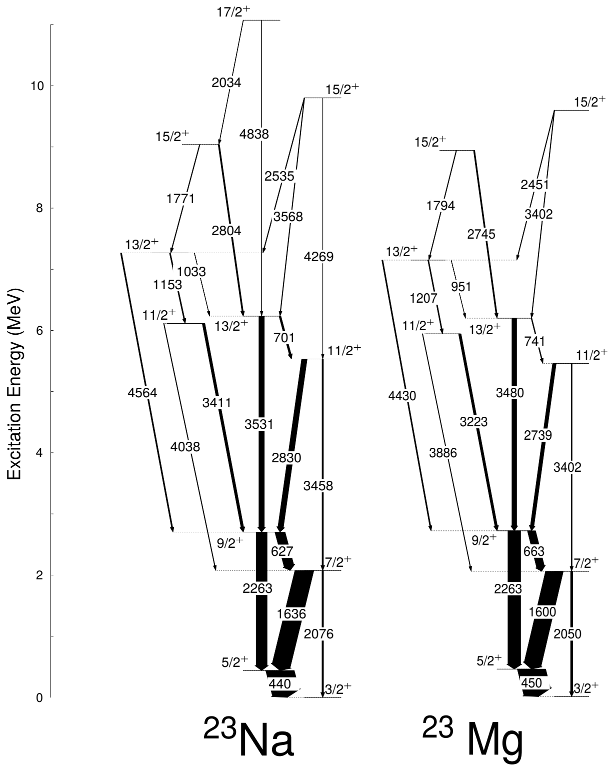

Fig. 1. Level schemes of mirror nuclei ^{23}Mg–^{23}Na deduced from this work. Only the most relevant transitions between positive parity states are reported.

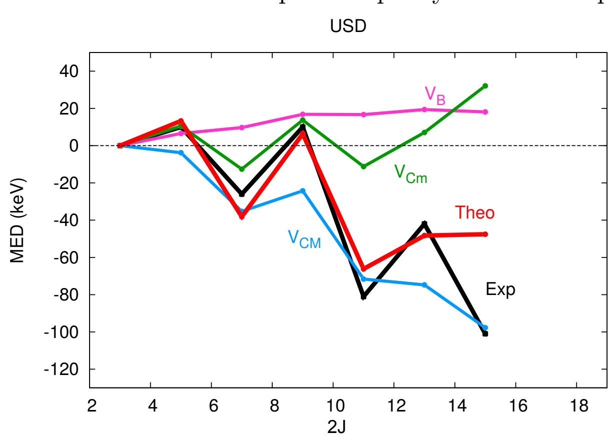

Fig. 2. Experimental and theoretical MED in mirror nuclei ^{23}Mg–^{23}Na obtained with the USD interaction. The ISB part V_B, the radial contribution V_{Cm} and the multipole term V_{CM} are enlightened.

orbit in this mass region. It has been recently argued that the $s_{1/2}$ orbit extends ~ 1.5 fm more than the d orbitals [8], which implies a sizeable effect on the nuclear radius and on the MED when nucleons move from the former to the latter orbit and *vice versa*. The contribution of the nuclear ISB term V_B does not follow the experimental trend and seems to be not needed to achieve a good theoretical description of the data. This suggests a different role of the $J = 2$ *Anomaly* in the $A = 23$ nuclei with respect to the case in the $f_{7/2}$ shell.

To further investigate this issue, an alternative approach has been adopted. The monopole corrected MCI interaction [5], derived from the realistic nucleon–nucleon N3LO potential [6], has been used in a no-core space. In this framework, the Coulomb multipole term, the corrections to the single-particle energies and the nuclear ISB contribution are naturally taken into account in the interaction. In the shell model calculations, different potential wells have been used for protons and neutrons following Ref. [8]. The $\hbar\omega$ of the harmonic oscillator potential is related to the nuclear radius by the expression: $\hbar\omega_\pi = \frac{41.47}{\langle r_\pi^2 \rangle} \sum_i m_i(p_i + 3/2)/A$, where m_i and p_i are the total occupancy and principal quantum number of the orbit i. The proton radii ρ_π of ^{23}Na and ^{23}Mg have been obtained from the fit of the experimental data following the Duflo–Zuker approach [7]. The fit has been optimized to reproduce the difference in the binding energy between the mirror nuclei. The isospin symmetry implies that the proton radius of the $Z < N$ nucleus is equal to the neutron radius of its mirror, which allows to obtain the neutron radii ρ_ν for both nuclei. The $\hbar\omega$ for each fluid has been obtained from the corresponding radius, implying a different interaction for each nucleus. The radial term V_{Cm} has been derived from the occupation numbers of the $s_{1/2}$ orbit as described above. The results of the calculations are reported in Fig. 3 together with the experimental data.

Shell model calculations using the MCI interaction follow very well the trend of the experimental MED. This remarkable result shows the possibility to reproduce the data using a realistic no-core interaction which already includes all the relevant ISB terms. On the other hand, it is still clear how the inclusion of the radial term V_{Cm} is crucial to improve the theoretical description, further confirming the fundamental role of the $s_{1/2}$ shell in the evolution of radii in this mass region [9]. The disagreement between theory and data at $J = 15/2^+$ could be due to the fact that the actual wave function includes configurations involving excitations to the fp shell, not considered in the present calculation. Further investigations on this subject are in progress. The validity of this approach will be tested in other mirror nuclei in the sd shell.

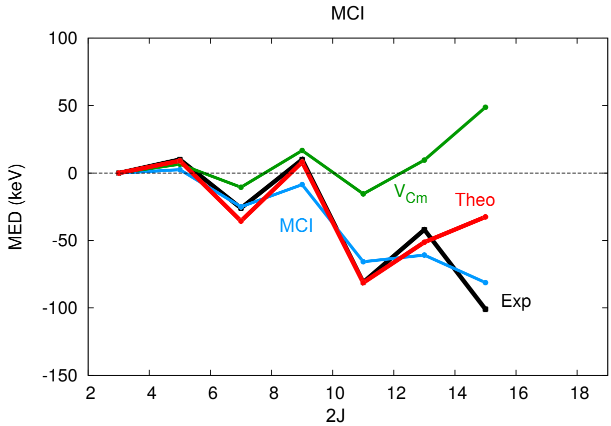

Fig. 3. Experimental and theoretical MED in mirror nuclei ^{23}Mg–^{23}Na obtained with the MCI interaction. The radial term V_{Cm} and the MCI contribution are enlightened.

REFERENCES

[1] A.P. Zuker, S.M. Lenzi, G. Martínez-Pinedo, A. Poves, *Phys. Rev. Lett.* **89**, 142502 (2002).

[2] S.M. Lenzi *et al.*, *Phys. Rev. Lett.* **87**, 122501 (2001).

[3] M.A. Bentley, S.M. Lenzi, *Prog. Part. Nucl. Phys.* **59**, 497 (2007).

[4] D.G. Jenkins *et al.*, *Phys. Rev. C* **87**, 064301 (2013).

[5] A.P. Zuker, "Monopole Corrected Interactions", unpublished, 2016.

[6] D.R. Entem, R. Machleidt, *Phys. Lett. B* **524**, 93 (2002).

[7] J. Duflo, A.P. Zuker, *Phys. Rev. C* **66**, 051304 (2002).

[8] J. Bonnard, S.M. Lenzi, A.P. Zuker, *Phys. Rev. Lett.* **116**, 212501 (2016).

[9] J. Bonnard, A.P. Zuker, `arXiv:1606.03345 [nucl-th]`.